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Reducing greenhouse gas emissions while maintaining yield in the croplands of Huang-Huai-Hai Plain, China

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ABSTRACT

Agroecosystems face double pressures of producing more food to feed growing global population and reducing greenhouse gas (GHG) emissions to mitigate climate change. The Huang-Huai-Hai (HHH) plain produces ~1/3 wheat and maize of China with very high resource inputs, particularly synthetic nitrogen (N) fertilizers since the 1980 s. Although fertilizer input has substantially increased crop yield and enhanced biomass carbon (C) input to the soil and thus stimulating soil C sequestration, GHG emissions (e.g., nitrous oxide (N_2O)) relating to the fertilizers have been also dramatically increased. Yet, a systematic regional assessment on the trade-offs between crop yield, soil C sequestration and N_2O emissions as impacted by management practices and environmental conditions is lacking. Here we calibrated a farming system model to conduct comprehensive assessment on crop yield and GHG emissions (soil CO_2 and N_2O emissions) during the period 1981–2010 across the HHH plain at the resolution of 10 km. We found that soil in HHH plain was a C sink with an annual C sequestration rate of 1.53 CO_2-eq ha^{-1} yr^{-1} (0–30 cm soil layer) during the period under current typical agricultural practices, but this sink could only offset about 68% of global warming potential from contemporary N_2O emissions. By reducing the annual N input rate (from current more than 300 to ~250 kg N ha^{-1} yr^{-1}) and enhancing crop residue retention rate (from current 30% to 100%), the HHH plain could act as a net sink of GHG without sacrificing grain yield. Apart from management, the effects of three key environmental factors, i.e., mean annual rainfall and temperature and initial soil organic carbon stock on dynamics of crop yield, soil CO_2 and N_2O emissions were also studied. The results will have important implications for the development of management strategies to maintain yield while reducing GHG emissions.

1. Introduction

Global agricultural intensification has induced significant environmental problems such as soil acidification and degradation, water eutrophication and greenhouse gas (GHG) emissions (Horrigan et al., 2002; Moss et al., 2008). Among the GHGs, soil carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions are dominant in dryland cropping systems. Up to half of the soil organic carbon in the top 30 cm soil can be emitted to the atmosphere as CO_2 after land clearing for agricultural production. For N_2O emissions from agroecosystems, they contribute around 60% to the global N_2O emissions, mainly induced by the use of synthetic nitrogen (N) fertilizers (Smith et al., 2007; Zhang et al., 2014). In the context of global change, modern agriculture faces a big challenge to not only produce enough food to feed increasing global population but also reduce environmental footprints, particularly greenhouse gas (GHG) emissions (Bradford et al., 2016). To overcome this challenge, we need a detailed understanding of the response of crop production and GHG emissions to various management practices, therefore facilitating development of win-win management strategies.

Nitrogen fertilizer application plays a core role in determining crop yield as well as GHG emissions. Crop yield generally increases with N fertilizer application rates until reaching a plateau (Fig. 1). Beyond this plateau, additional N inputs will lead to no yield benefits, while resulting in tremendous N_2O emissions and other sources of N loss from the agricultural systems. In China, agroecosystems are intensively managed with very high N fertilizer inputs. During the period 1981–2010, the use of synthetic N fertilizers was increased from 10.9 Tg yr^{-1} in the earlier 1980 s to 28.1 Tg yr^{-1} in the later 2000 s (Zhang et al., 2014), while the N use efficiency has decreased (Ju et al., 2009; Liu and Diamond, 2008). For example, Ju et al. (2009) reported that increased N use across the North China Plain did not significantly increase crop yields but caused two times larger N losses to the

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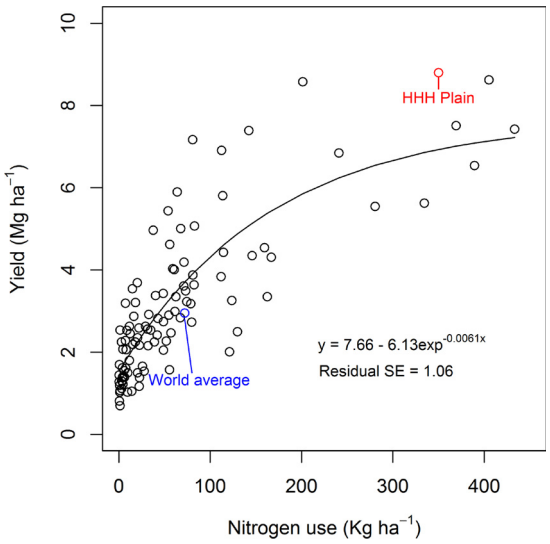

Fig. 1. The global-scale impact of nitrogen use on cereal crop yield on a country level from 2006 to 2010. The data for Huang-Huai-Hai Plain (red circle) is sum of the regional average yields of maize and wheat (the two main staple food crops in this region), which was derived from Zhang et al. (2014). The global country-level data (black circles) was obtained from FAOSTAT (http://faostat3.fao.org/home/E) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

environment. The rapid increase of N fertilizer inputs has caused a rapid increase in N_2O emissions that has outstripped the enhancement in crop production (Zhang et al., 2014; Tian et al., 2011; Lu and Tian, 2013; Tian et al., 2012). For example, the average N input rate in the Huang-Huai-Hai (HHH) Plain has exceeded 300 kg ha^{-1} which is much higher than some regions with the similar levels of crop yield (Fig. 1). Although this high level of N use can ensure high cereal yield (Fig. 1), it also causes serious environmental problems including dramatically enriched N_2O emissions (Ju et al., 2009). In a field trial in the HHH region, Yan et al. (2015) reported that increasing N use rate from 420 to 600 kg ha^{-1} yr^{-1} resulted in 50% increase in annual N_2O emissions without increment in crop yields. These results highlight that sustainable agriculture intensification should take into account the negative effect of N fertilizers on environment such as GHG emissions.

Apart from N fertilization, crop residue management and manure application (i.e., organic amendments) complicate the assessment on the trade-offs between crop production and GHG emissions (Wang et al., 2014b). It is possible that the mineralization of organic amendments may release N for crop growth and thus reduce the requirement of synthetic N. On the contrary, organic amendments (they usually have high C:nutrient ratios) may be stabilized to form new SOC (they usually have low C:nutrient ratios), i.e., carbon sequestration, and thus require additional nutrient including N to maintain stoichiometric balance. The long-term magnitude and direction of the effects of organic amendments on N management, crop yield and GHG emissions depends on the quantity and quality of organic amendments, other management and climate and soil conditions, which is needed to be quantified using a systematic approach.

Modelling approaches have already been used to quantitatively assess both crop production and the associated environmental footprints in response to different agronomic management, particularly the use of chemical N fertilizers (Tian et al., 2012; Lu and Tian, 2013). For example, based on simulations with an Earth system model (i.e., DLEM), Lu and Tian (2013) reported that N-induced N_2O emissions has offset the benefits from soil C sequestration in N overused areas of China. By contrast, using the same model, Tian et al. (2012) suggested that reducing current N fertilizer level by 60% in the 'over-fertilized' areas can substantially decrease N_2O emission without significantly influencing crop production. However, the detailed agronomic management such as planting, harvesting, fertilizing, crop residue management, manure incorporation and irrigation can hardly well represented by Earth system models because of the complexity in implementation and the large uncertainty at the global scale (Samuel, 2014). A process-based farming system model with implementing these detailed complex processes can potentially be used to more accurately simulate crop productivity, nutrient cycling and environmental impacts as influenced by environmental variability and management interventions. For example, Zhang et al. (2014) used an agricultural production model to quantify the net GHG emissions in China's croplands by considering specific temporally varied rates of crop residue retention, manure and nitrogen applications. However, there still lacks a comprehensive, high resolution strategic assessment on the potential of maintaining crop production and soil organic carbon accumulation while reducing GHG emissions through improving agronomic management across the high nutrient input and GHG emission regions in China.

In this study, we first calibrated the performance of the Agricultural Production System sIMulator (APSIM) in simulating crop yield and SOC dynamics in HHH plain. And then the calibrated APSIM was used to simulate the crop growth and soil nutrient cycling of the winter wheat-summer maize double cropping system across the whole HHH plain. The HHH plain in China is a typical region with intensive agricultural management involving N fertilizers, organic manure application and crop residue retention, providing a good opportunity to characterize the detailed spatial patterns and explicitly evaluate the relationships between N use, crop yield and soil CO_2 and N_2O emissions at the regional scale. Specifically, the objectives of this study were to: 1) assess the crop production, soil C sequestration and N_2O emissions during the past three decades; 2) target potential opportunities for maintaining crop production with maximum reduction in GHG emissions; and 3) identify the key management and environmental factors regulating yield and GHG emissions.

2. Materials and methods

2.1. Study region and long-term experimental sites

This study focuses on the croplands across the Huang-Huai-Hai Plain in China (Fig. 2). The HHH Plain includes the areas of five provinces and two municipalities: the entire Shandong, major parts of Hebei, Beijing and Tianjin and Henan; and the northern parts of Anhui and Jiangsu. The croplands in this region constitute around one-six of China's total cultivated area, and produce 35–40% and 60–80% of China's wheat and corn (Liu et al., 2015), respectively. Consequently, the HHH Plain is described as the "food bowl" of China (Kong et al., 2014).

Data from three long-term experimental sites (Fig. 2 and Table 1) located within the HHH Plain as a part of the National Long-term Fertilisation Experimental Network in China (Zhao et al., 2010) were used to constrain the APSIM model for accurately simulating soil organic carbon changes and crop productions under various management practices. Data from another two-year field experiment at Huantai (Table 1) was used to test the model's performance in simulating soil N_2O emissions. The mean annual temperature and precipitation at these sites varies from 11 to 15 °C and from 547 to 848 mm, respectively. The initial soil organic carbon stock varies from 20 to 40 Mg C ha^{-1} (0–30 cm soil profile). The multi-year average crop yields vary from 4.8 to 7.4 Mg ha^{-1} for maize and from 3.8 to 6.3 Mg ha^{-1} for wheat, respectively, under the farmers' conventional management practices. Both soil and land use history at the three sites are representative of the HHH plain. The double cropping system of winter wheat and summer maize were adopted at these sites, which is in line with the typical cropping practices in the croplands of the HHH Plain. In general, among these sites, several treatments involving synthetic nitrogen fertilization, manure application and crop residue retention were included in the

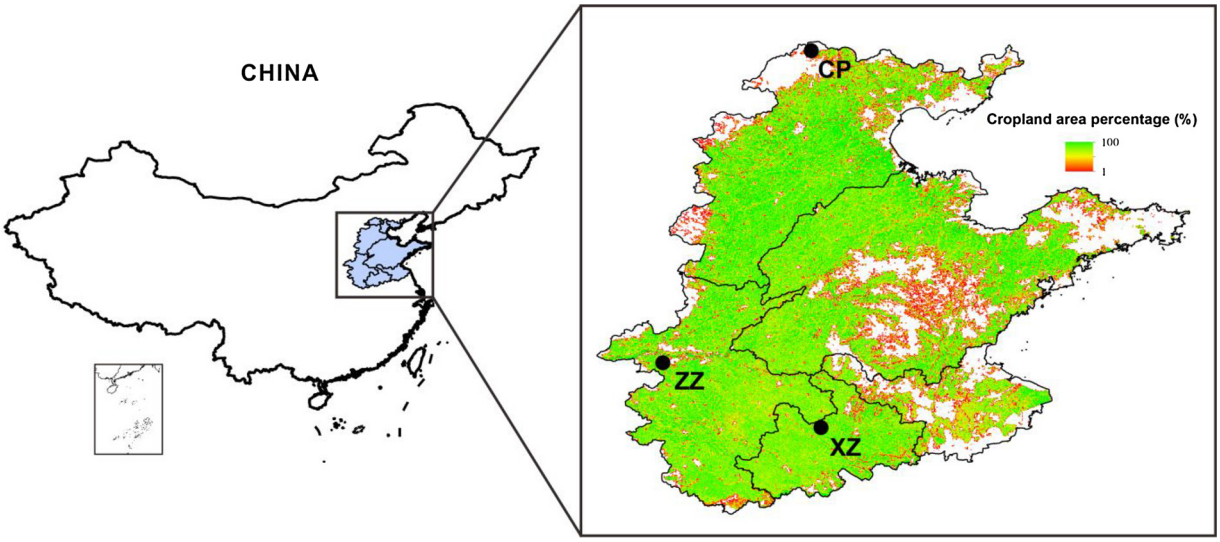

Fig. 2. The spatial distribution of the croplands in the Huang-Huai-Hai (HHH) Plain. The inner lines show the provincial boundaries and the dots show the sites for model constraining. CP: Changping Site; ZZ: Zhengzhou Site; XZ: Xuzhou Site. The spatial boundaries of the HHH Plain were acquired from the report of Liu et al. (2015).The spatial distribution of croplands was computed based on the National Land Cover Data Sets (NLCD) of China, developed from Landsat TM digital images around the year 2000 (Liu et al., 2003).

experiments. Table 1 summarizes the climate and soil conditions and the crop yield information at each study site. Detailed information on the experiment design and data can be found in Zhang et al. (2010); Wang et al. (2015) and Li et al. (2016b).

2.2. The APSIM model

We used the Agricultural Production Systems sIMulator version 7.5 (APSIM) to simulate crop yield, soil C dynamics and N_2O emissions of the wheat-maize cropping systems in the HHH Plain. APSIM is a process-based model simulating crop growth and soil processes on a daily time-step in response to climatic and edaphic status and agricultural management practices (Holzworth et al., 2014; Keating et al., 2003). During the past several decades, numerous studies have found that the model is able to reasonably reproduce the crop growth (Asseng et al., 1998; Meinke et al., 1997; Wang et al., 2003) and soil C dynamics (Luo et al., 2015; Probert et al., 2005) under a wide range of environmental and anthropogenic conditions including in the HHH plain (Wang et al., 2014a, 2009). Recently, Gaydon et al. (2017) evaluated the model's performance using observations collated from 12 countries in Asia, and found that once properly parameterised, the model performed well in simulating crop production and soil water and nutrient processes across a diversity of cropping systems. At the regional scale, Wang et al. (2015) parameterized the APSIM model using data from three long-term agricultural experimental sites (i.e., crop yield and soil C dynamics) and simulated the regional cropland soil C changes in response to variations of climate and agronomic practices in North China Plain (the spatial distribution of which is similar to HHH Plain). In the present study, we adopted the APSIM model's default crop related parameters (e.g., root:shoot ratios and C:N ratios), and further calibrated the performance of the APSIM model in simulating SOC dynamics using observational data collected across the HHH Plain (see the *Model constraining* section).

In APSIM, the dynamics of C and N in each soil layer depth were simulated using a framework similar to that used in other C dynamic models such as RothC (Jenkinson et al., 1990). The model divides soil organic matter into three conceptual pools: fresh organic matter (FOM, further split into three sub-pools), a more active carbon pool (BIOM) and a humic pool (HUM). In each pool and sub-pool, the decomposition of C follows a first-order decay process. A specific maximum C decomposition rate constant is pre-defined for each C pool, which is further modified by temperature, moisture and nutrient availability (Thorburn et al., 2001). The C decomposition results in release of CO_2 to the atmosphere and transferring of the remaining decomposed C to other pools. The processes involved with N mineralisation, immobilisation, nitrification, denitrification, leaching and runoff are also simulated by the model (Probert et al., 2005; Thorburn et al., 2010). In APSIM, denitrification is computed as a function of NO_3– amount, active C concentration, soil temperature and moisture (Thorburn et al., 2010). N_2O emissions *via* denitrification are then calculated as a fraction of total denitrified N using a ratio of N_2 to N_2O emitted during denitrification (Del Grosso et al., 2000). Nitrification is determined by Michaelis-Menten kinetics and modified by soil pH, soil moisture and temperature and N_2O emissions *via* nitrification is estimated as a

Table 1
Summary of the field experimental observations.

Site	Latitude (N)	Longitude (E)	MAT[1] (°C)	MAP[2] (mm)	Time span	Initial SOC[3] (Mg C ha^{-1})	Crop yield[4] (Mg ha^{-1})		N_2O emission[5] (Kg N ha^{-1} yr^{-1})
							Maize	Wheat	
Xuzhou	33°39′	116°22′	15	848	1980-2003	20	6.8	5.9	NA
Zhengzhou	34°47′	113°39′	15	632	1990-2003	22	6.2	6.3	NA
Changping	40°13′	116°12′	11	600	1990-2005	26	4.8	3.8	NA
Huantai	36°58′	117°59′	14	547	2008-2010	40	7.4	6.1	4.6

[1]MAT: mean annual temperature. [2]MAP: mean annual precipitation. [3]The initial soil organic carbon stock at the 0–30 cm soil profile. [4]The multi-year average crop yield under the farmers' conventional management practices, normally with relatively high nutrient inputs. [5] The multi-year average annual N_2O emission under the farmers' conventional management practices. NA: not available.

fraction of the nitrified N (= 0.002) (Li et al., 2007). More details on nitrification and denitrification processes simulated by the APSIM model are described by Thorburn et al. (2010). Using two years of experimental data of crop yield and N_2O emissions at Huantai (located in the HHH Plain), we have previously tested the APSIM model's performance in simulating N_2O emissions from soil in response to water and nutrients management practices (Li et al., 2016b). The relevant model parameters were adopted to simulate N_2O emissions in this study. This is reasonable because the agricultural soil in the HHH plain is almost homogeneous and the same cropping system was simulated. As such it is, we acknowledge that more observed N_2O emission data is required in order to better constrain the APSIM model.

2.3. Model constraining and uncertainty analysis

Observational data from nine agricultural trials at the above-mentioned three sites (Fig. 2) were used to constrain the APSIM model. The experimental duration of these trials ranges from 14 to 24 years; the experiments cover diverse climate, soil and agricultural management conditions, are representative of the wheat-maize cropping system in the HHH Plain and are located in the study region (Fig. 2). Each trial includes a detailed records on crop phenology and yield and agricultural management practices such as the amount and time of residue retention and fertilizer and manure application for each year. Soil properties at the start of the experiments were also measured, including total carbon and nitrogen content, bulk density, clay content and pH, which were used to initialize the APSIM model. We aimed at simulating the SOC stock in the top 30 cm soil profile and used the observed SOC to constrain the model. Following Luo et al. (2015), three model parameters that are the key edaphic parameters regulating SOC dynamics, the coupled nitrogen dynamics and crop growth, were optimized using a Bayesian optimization approach. The three parameters are the fraction of inert organic carbon (*finert*), the decomposition rate of humic organic carbon (k_{hum}) and the microbial carbon use efficiency (*CUE*). First, for each parameter, we assumed an empirical uniform distribution bounded with a range (0–1 for *finert*, 0.0015–0.000015 day^{-1} for k_{hum} and 0.2–0.8 for *cue*) that is biologically and physically possible based on existing knowledge. Then, the model was optimized using a differential evolution algorithm for global optimization (Mullen et al., 2009) to best match the observations. The mean residual sum of squares was minimized to target the best agreement between model predictions and observations. Finally, the best 100 pairs of model parameters (Table A.1) were used in the regional scenario simulations to analyse the parameterization-derived uncertainties in both GHG emissions and crop yield production. The mean and 95% confidence intervals (i.e., parameterization-induced uncertainty) for the simulated crop yield, soil organic carbon change and N_2O emissions were calculated and reported.

2.4. Spatial data

Across the HHH Plain, the spatial variations in crop yield, soil organic carbon (SOC) and nitrous oxide (N_2O) emissions in response to climatic and edaphic conditions and management scenarios were simulated with a daily step from 1981 to 2010 using the APSIM model. Firstly, we rasterized the model inputs of climate data (e.g., daily air temperature, precipitation and radiation), soil properties (e.g., initial soil properties at each soil depth (e.g., soil organic carbon content, total nitrogen content, pH and soil water attributes et al.) and agricultural management information into 10 km × 10 km gridded datasets across the study area (Fig. A1 in Appendix A). Then, the APSIM simulations were performed grid by grid across the study area using the gridded model inputs.

The APSIM requires parameters that describe the initial soil physical and chemical properties (e.g., initial soil water and nutrient conditions). These soil properties, including soil organic carbon, nitrogen, bulk density, clay fraction, pH, saturated water content (SAT), drained upper limit (DUL), lower limit of crop water extraction (LL), with a 10 km × 10 km spatial resolution, were obtained from the China Soil Scientific Database (CSSD) (Yu et al., 2007), which represents more than 7000 soil profile measurements across China made in the late 1970s/early 1980s. This spatial dataset of soil properties has already been widely used for modeling (Yu et al., 2012; Qin et al., 2013; Wang et al., 2014b). Climate data including temperature, precipitation and radiation is also required by APSIM for driving the model. The daily climatic variables from 1981 to 2010 at around 670 meteorological stations across China were firstly sourced from China Meteorological Administration. Then, we obtained the gridded climatic data across the study area by applying the interpolation algorithm (Thornton et al., 1997) to these site-level data and masking the yielded raster layers with the boundary of the HHH Plain (Fig. A1 in Appendix A). Details of the climate data sets were presented in our previous studies (Zhang et al., 2011, 2007).

2.5. Scenarios of agricultural management

In the HHH Plain, application of synthetic nitrogen fertilizers and manure and crop residue retention have been the key agronomic management influencing crop production, soil C dynamics and N_2O emissions (Ju et al., 2009; Wang et al., 2014b; Zhang et al., 2014). According to a database including county-level annual cultivation area and total synthetic N application amount (Wang et al., 2014b), the N fertilization rates in HHH Plain throughout the study period ranges from 130 to 450 Kg ha^{-1} yr^{-1} (95% confidence interval). Ju et al. (2009) reported a higher annual application rate of synthetic N for conventional agricultural practices in this area ranging from 550 to 600 Kg ha^{-1} yr^{-1}, which was based on site-level experimental observations. By taking manure application and N deposition into account, the actual N input rate in this region could even be much higher. According to another province-level database including farm manure application information in China (National Development and Reform Commission, 2007), manure (dry matter) application rate generally varied from 1000 to 4000 kg ha^{-1} (with a median value of around 2000 Kg ha^{-1}) across the HHH Plain over the study period. In China's rural areas, because of urbanization and the transformation in agriculture from small-scale household farming to large-scale farming operation, the investment and production of organic manure and its quantities being applied to cropland soils are decreasing (Gao et al., 2012). During the study period, China's average retention rate of crop straw was approximately 30%, with a general trend of increase over time (Jiang et al., 2012). Across the HHH Plain, this rate now ranges from ~ 40% to ~ 60% (Gao et al., 2009), and a higher rate is expected in the future due to the local governments' incentive programmes to encourage farmers to retain crop residues in the field for benefiting both soil fertility and crop production (Wilkes and Zhang, 2016).

With the consideration of general agricultural management described above, in order to quantify the effects of agricultural management practices on both crop yield and GHG emissions in the HHH plain, we simulated the crop growth, SOC changes and N_2O emissions under 56 combinations of N fertilization, manure application and residue retention rates. Management practices included 7 nitrogen application rates (0–600 kg N ha^{-1} yr^{-1} in 100 kg N ha^{-1} yr^{-1} increments, i.e., N0, N100, N200, N300, N400, N500 and N600). According to the local farmers' conventional practices (Wang et al., 2014b), apart from N0, we specified that 55% of the N fertilizers was applied during maize growing seasons, with the rest was applied during wheat growing seasons. For each growing season, 40% of the N were fertilized at crop emergence, another 40% at flowering, with the rest at heading for wheat and silking for maize, respectively. We also specified two manure application rates of 0 and 2000 kg ha^{-1} yr^{-1} (dry matter, denoted as M0 and M2000, N included in M2000 was roughly 45 kg ha^{-1} yr^{-1}) and four stubble retention rates of 0%, 30%, 60% and 100% (denoted as R0,

R0.3, R0.6 and R1). Among these management scenarios, the combination of N300, R0.3 and M2000 was most in line with common agricultural management practices throughout the study period that derived from statistical, survey and/or inventory databases, we called the simulations under this scenario the business-as-usual simulation.

2.6. APSIM simulations

We obtained 100 ensembles of optimized parameters that can equally well simulate observed SOC via the Bayesian optimization procedure, the APSIM model was run continuously from 1981 to 2010 using each parameter ensemble. As such, there are a total of 5600 simulations (100 parameters ensembles by 56 scenarios) for each 10 km × 10 km grid (3409 grids in total), resulting in ~20 million simulations. Except for the three optimized parameters, the values for all other soil parameters were derived from the CSSD database as described above. Because of the lack of detailed information on the crop cultivar across the region, we simply assumed that the same crop cultivars were used across the study area, and crop parameters were set as the same as the model constraining sites. Here, we acknowledge that the same cultivars may lead to some uncertainties in biomass production and thereby C inputs to the soil. Nevertheless, this would not be a significant issue as the dominant factors controlling biomass production are soil nutrient availability and climate conditions.

Sowing dates of maize and wheat were based on local crop calendars, which ranged from 6 June to 15 June for maize and ranged from 5 October to 11 November for wheat in the HHH Plain (Wu et al., 2006, 2008). The model ceases the crop growth at its physiological maturity that determined by the simulated maturity. Moreover, because of a lack of detailed irrigation information, we assumed that irrigation would bring soil moisture to field capacity when the soil moisture drops to 70% of the field capacity. This assumption is generally consistent with the irrigation management in the study region and has been widely adopted in other modeling studies (Wang et al., 2014b; Yu et al., 2012). It should be noted that N deposition from atmosphere has been reported to significantly contribute to nutrient budgets in most China's agro-ecosystems (He et al., 2010). According to a recent experiment-based work (Pan et al., 2012), the current N deposition rate was around 70 kg N ha^{-1} yr^{-1} across two agricultural systems in the HHH Plain. Consequently, apart from the synthetic N fertilization and manure application, we assigned this extra annual N input from the atmosphere (evenly distributed throughout the year) in our model simulations. To be summarized, the N input to the soils comes mainly from three sources: synthetic N fertilizers, manure and N deposition. For the business-as-usual management (N300, R0.3 and M2000), for example, the total N input was 415 kg N ha^{-1} yr^{-1} (300 kg N ha^{-1} yr^{-1} from synthetic N fertilizers, 45 kg N ha^{-1} yr^{-1} from manure and 70 kg N ha^{-1} yr^{-1} from N deposition).

2.7. Assessing the impacts of management and environmental factors on yield and GHG emissions

Based on the simulation results, we calculated the annual soil CO_2 and N_2O emissions in CO_2 equivalents (CO_2-eq) using the 100-year global warming potential of 298 for N_2O in each grid under each scenario. Annual soil CO_2 emission was calculated through dividing soil C change (i.e., the difference between soil C content in the starting year and that in the last year of the simulations) by the years of simulation. Positive and negative soil CO_2 emissions suggest the soil is a source or sink of atmospheric CO_2, respectively. Nitrous oxide emissions are summed by direct emissions from the soil via nitrification and denitrification processes (predicted by the APSIM model) and indirect emissions from atmospheric deposition of N volatilised from the soil as well as from N leaching/runoff (estimated using IPCC approach (De Klein et al., 2006). N_2O emissions from N volatilisation was calculated as: $N_2O_V = N \times F_V \times EF_V \times 44/28$, where N is the annual amount of synthetic N fertiliser and organic N being applied (kg N yr^{-1}), F_V (= 0.1) is the fraction of total N input that volatilised as NH_3 and NO_x (kg N volatised per kg N applied), EF_V (= 0.01) is the emission factor for N_2O emission resulting from the N volatilisation (kg N-N_2O per kg N volatised). Emissions from N leaching/runoff were computed as: $N_2O_L = N_L \times EF_L \times 44/28$, where N_L is the amount of N leaching/runoff which is estimated by the APSIM model (kg N yr^{-1}) and EF_L (= 0.0075) is the emission factor for N_2O emission resulting from the N leaching/runoff (kg N-N_2O per kg N leached and runoff). The annual net GHG emission was then calculated as the sum of annual soil CO_2 and N_2O emissions in CO_2 equivalents (CO_2-eq). Positive and negative CO_2-eq represents a net source and sink of atmospheric CO_2-eq, respectively.

We investigated the effects of synthetic N fertilization on crop yield, soil CO_2 emission (negative emissions indicate soil carbon gain and *vice versa*), N_2O emission and net GHG emission by producing boxplots quantitatively characterizing the impacts of N management on these variables under typical management scenarios. Under different N fertilization treatments (0–600 kg ha^{-1} yr^{-1}), the mean annual crop yields, soil CO_2 emission, N_2O emission and net GHG emission were calculated and fitted using the nonlinear least squares method characterizing the response of these variables to management practices. Based on the scenario simulation results and the fitted nonlinear relationship between N input rates and the corresponding crop yields and CO_2 and N_2O emissions, two targets involving these variables were determined: 1) 90% of the maximum crop yield and 2) minimum soil CO_2 and N_2O emissions. The 90% of the maximum simulated yield was selected because productions above this figure are associated with significantly diminished economic return (Carberry et al., 2013).

Apart from agronomic management practices, environmental conditions including soil and climate also regulate the dynamics of crop yield and GHG emissions (Luo et al., 2017; Wang et al., 2014b). Three key attributes: annual average rainfall (*Rain*), temperature *(Temp*) and initial soil organic carbon stock (*Initial C*) were focused in the present study. These three attributes have been suggested having significant effect on crop yield and GHG emissions in other regions (Luo et al., 2017). Here, Spearman's rank correlation coefficient (*rho*) was analysed to address the correlation between the crop yield, soil CO_2 emission, N_2O emission and the three environmental factors. The nonparametric Spearman's rank correlation coefficient was preferred as it is robust to departure from the normal distribution commonly found in the three variables. The sign of *rho*, positive or negative, indicates the direction of the association between the independent variables and the dependent variable. The absolute magnitude of *rho*, between 0 and 1, indicates the strength of the correlation between the two variables. All analyses were performed using statistical and graphical software R 3.4.2 (R Development Core Team, 2017).

3. Results

3.1. Model performance

The APSIM model could reasonably simulate the grain yield of winter wheat and summer maize when all data are put together (Fig. 3a). Generally, APSIM could explain around 60% and more than 70% of the variations in the grain yield of maize and wheat, respectively, caused by different management practices regarding residue retention, manure application and synthetic N fertilization at the three long-term experimental sites. For the soil C dynamics, the APSIM model was well constrained for simulating observed SOC stock in the top 30 cm soil layer (Fig. 3b). Pooling together all data of the 9 trials at the three experiments, the constrained APSIM model could explain 87% ($P < 0.001$) of the variances in observed SOC (Fig. 3b). Using the 100 ensembles of the three parameters (Table A1 in Appendix A), model performance was nearly identical evidenced by the very small error bars in Fig. 3b. At the site scale, the APSIM model has been proved to

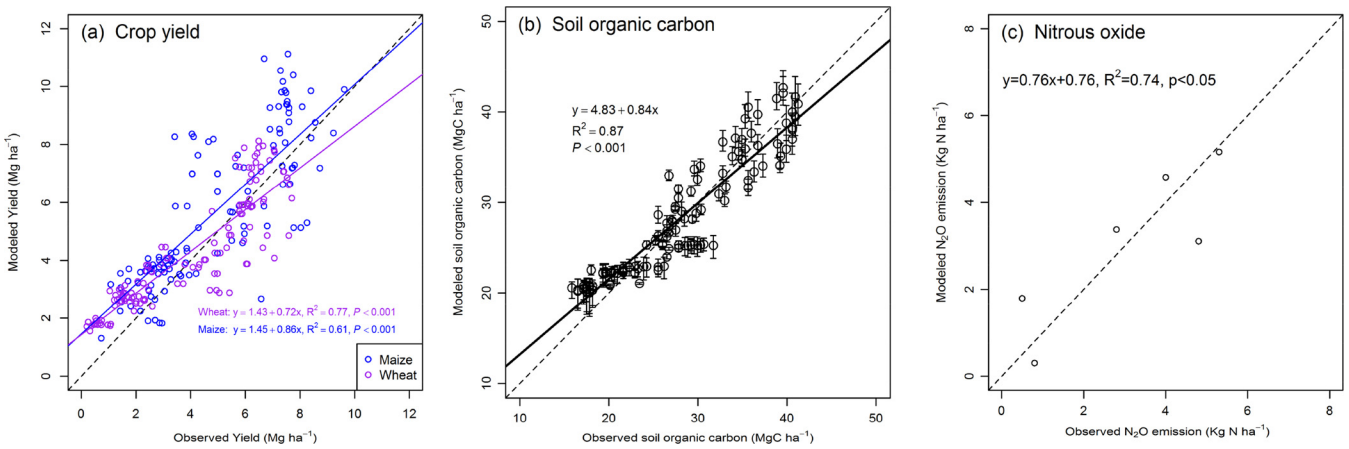
(a) Crop yield
Modeled Yield (Mg ha^{-1})
Observed Yield (Mg ha^{-1})
Wheat: y = 1.43 + 0.72x, R^2 = 0.77, P < 0.001
Maize: y = 1.45 + 0.86x, R^2 = 0.61, P < 0.001
Maize
Wheat
(b) Soil organic carbon
Modeled soil organic carbon (MgC ha^{-1})
Observed soil organic carbon (MgC ha^{-1})
y = 4.83 + 0.84x
R^2 = 0.87
P < 0.001
(c) Nitrous oxide
Modeled N$_2$O emission (Kg N ha^{-1})
Observed N$_2$O emission (Kg N ha^{-1})
y=0.76x+0.76, R^2=0.74, p<0.05

Fig. 3. Modelled and observed crop yield (a) and soil organic carbon (b) in 9 trials at three model constraining points and the nitrous oxide emissions at Huantai site (c). The data of nitrous oxide (c) were reproduced from our previous study (Li et al., 2016b). Dashed line shows the 1:1 line. Bars show the corresponding 95% confidence intervals of 100 simulations of SOC using the 100 ensembles of parameters shown in Table S1. k_{hum}, the decay constant of the humic organic matter; *finert*, the fraction of inert organic matter in total soil organic matter; *CUE*, the use efficiency of carbon by microbes. Dashed line shows the 1:1 line.

have the capacity to reasonably capture the annual N_2O emissions (Li et al., 2016b), and the model could averagely explain 74% of the annual cumulative N_2O emissions under various treatments although the N_2O data is very limited (Fig. 3c).

3.2. GHG emissions under business-as-usual management

Under the business-as-usual management (i.e., N300, R0.3 and M2000), the simulated average (1981–2010) soil CO_2 emissions (negative emissions indicate soil carbon gain and *vice versa*) across the HHH Plain were -1.53 (-2.18 – -1.25, 95% confidence interval, hereafter the same) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 4a) and the average N_2O emission were 2.23 (1.74–2.75) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 4b). As a sum, the average net GHG emissions including soil CO_2 and N_2O was 0.70 (-0.08 – 1.33) Mg CO_2-eq ha^{-1} yr^{-1}, and the net GHG emission seems decreased from north western to south eastern areas of the study region (Fig. 4c).

3.3. Uncertainty analysis

For the business-as-usual management simulations, the uncertainty (based on the 100 model simulations using different ensembles of parameters provided in Table A1 in Appendix A) analysis showed that the lower and upper limits of the 95% confidence interval in soil CO_2 emission (negative emissions indicate soil carbon gain and *vice versa*) across the HHH Plain were -1.71 (-2.37 – -1.47) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5a) and -1.41 (-2.06 – -1.05) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5d), respectively, under the business-as-usual management. The lower and

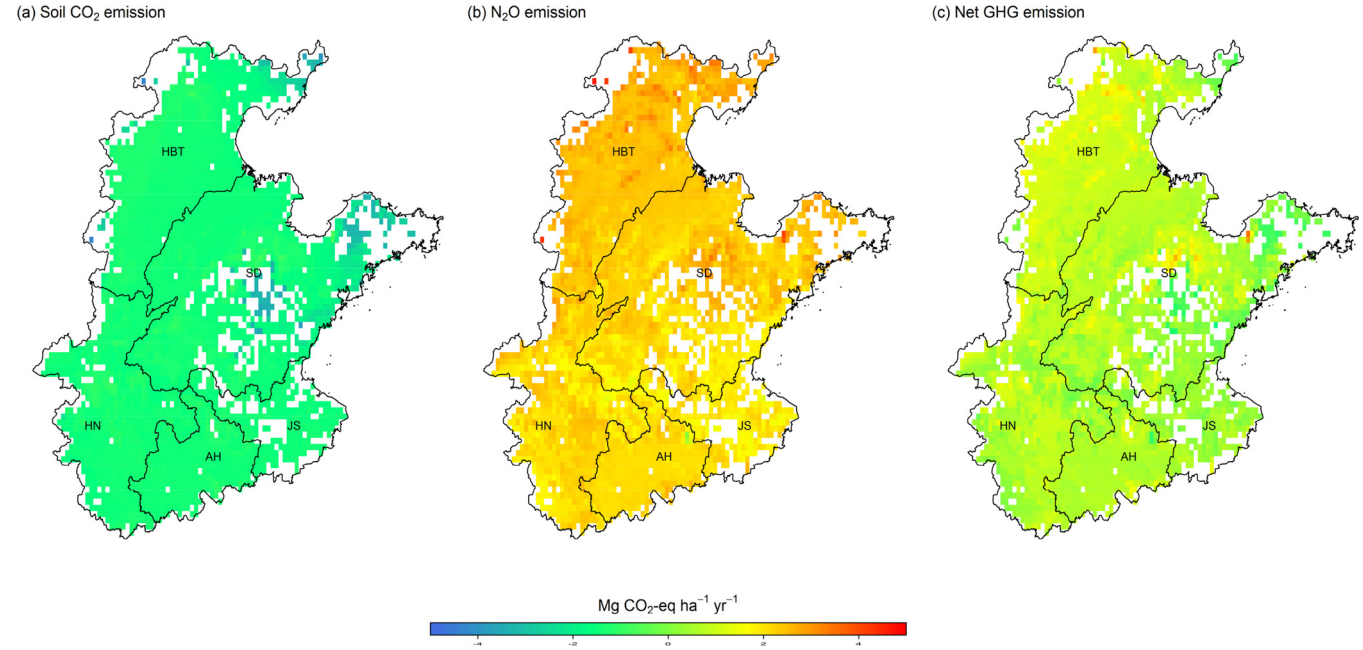

Fig. 4. Spatial distribution of the average soil CO_2 (a), N_2O (b) and the net GHG emission (c) from 1981 to 2010 under the business-as-usual management. The soil CO_2 emission is the annual soil C loss in terms of CO_2-eq ha^{-1} yr^{-1}, positive and negative soil CO_2 emissions indicate the soil acted as a net source and sink of atmospheric CO_2. The business-as-usual management is defined as a combination of N fertilization rate with 300 kg N ha^{-1} yr^{-1} (N300), stubble retention rate with 30% (R0.3) and manure application rate with 2000 kg ha^{-1} yr^{-1} (M2000). Apart from the synthetic N fertilization, additional N input from manure application (45 kg N ha^{-1} yr^{-1}) and N deposition (70 kg N ha^{-1} yr^{-1}) are adopted. The black lines for the HBT, SD, HN, AH and JS refer to the administrative regions of Hebei-Beijing-Tianjin, Shandong, Henan, Anhui, and Jiangsu, respectively.

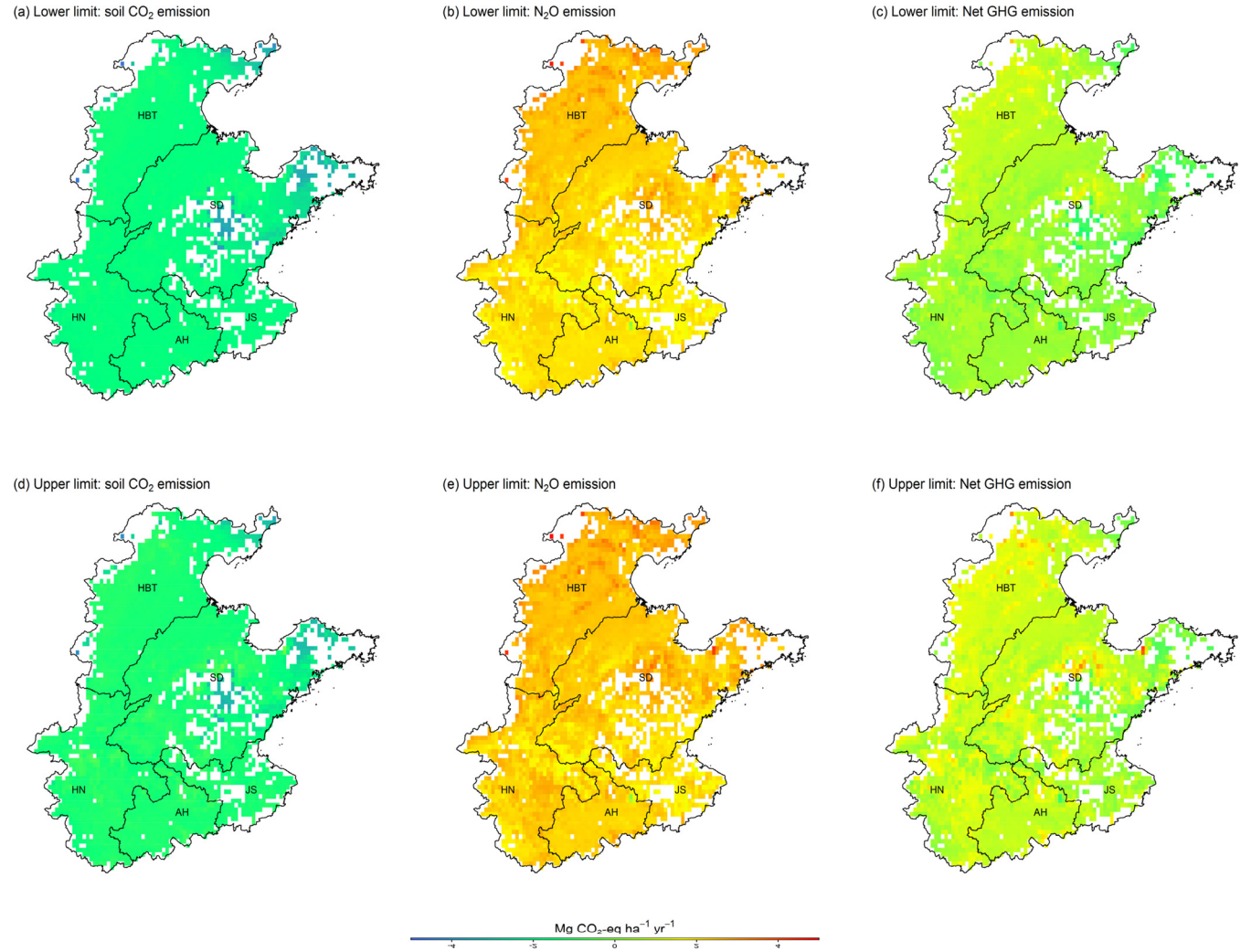

Fig. 5. Lower and upper limit of the 95% confidence intervals in the model quantified soil CO_2, N_2O and the net GHG emission from 1981 to 2010 under the business-as-usual management. The soil CO_2 emission is the annual soil C loss in terms of CO_2-eq ha^{-1} yr^{-1}, positive and negative soil CO_2 emissions indicate the soil acted as a net source and sink of atmospheric CO_2. (a) – (c) lower limits, (d) – (f) upper limits. The 95% confidence intervals were estimated from the 100 model simulations using the 100 ensembles of parameters (Table S1). The business-as-usual management is defined as a combination of N fertilization rate with 300 kg N ha^{-1} yr^{-1} (N300), stubble retention rate with 30% (R0.3) and manure application rate with 2000 kg ha^{-1} yr^{-1} (M2000). Apart from the synthetic N fertilization, additional N input from manure application (45 kg N ha^{-1} yr^{-1}) and N deposition (70 kg N ha^{-1} yr^{-1}) are adopted. The black lines for the HBT, SD, HN, AH and JS refer to the administrative regions of Hebei-Beijing-Tianjin, Shandong, Henan, Anhui, and Jiangsu, respectively.

upper limits of the 95% confidence interval in N_2O emission were 2.15 (1.68–2.68) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5b) and 2.31 (1.79–2.83) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5e), respectively. For the net GHG emission, the lower and upper limits of the 95% confidence interval were 0.45 (-0.25 – 1.07) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5c) and 0.89 (0.06–1.59) Mg CO_2-eq ha^{-1} yr^{-1} (Fig. 5f), respectively. Similar to the average values, the lower and upper limits of the 95% confidence interval of the net GHG emission decrease from north western to south eastern parts of the study region (Fig. 5c and f).

3.4. Scenario analysis

The scenario simulation results suggested that, under R0.3 and M2000, N fertilization increased the average crop yield most significantly ($P < 0.05$) at rates between 0 and 300 kg ha^{-1} yr^{-1}, with a limited effects at higher fertilization rates (Fig. 6a). On average of the HHH Plain, the highest crop yields reached around 11.2 Mg ha^{-1} at a N fertilization rate reaching to 300 kg ha^{-1} yr^{-1}, and a 90% amount of the maximum yield can be attained at a synthetic N rate of 132 kg ha^{-1} yr^{-1} (data not shown, with additional N input of 115 kg ha^{-1} yr^{-1} from N deposition and manure application). Under the same management scenario of crop residues and manure, the use of N fertilization between the rates of 0 and 200 kg ha^{-1} yr^{-1} seems linearly reduce the average soil CO_2 emission from -1 to -1.5 CO_2-eq ha^{-1} yr^{-1}, this influence was no longer significant at N rates higher than 300 kg ha^{-1} yr^{-1} (Fig. 6b). The increase in use of N fertilization resulted in exponential increase of average N_2O emissions from 0.15 to 5.6 CO_2-eq ha^{-1} yr^{-1} from N0 to N600 (Fig. 6c). The average net GHG emission were remained negative when N fertilization rate was not higher than 200 kg ha^{-1} yr^{-1}, ranging from ~ -0.85 CO_2-eq ha^{-1} yr^{-1} under N0 and N100 to -0.42 CO_2-eq ha^{-1} yr^{-1} under N200 (Fig. 6c). From N300 to N600, the average net GHG emission increased from 0.7 to 4.1 CO_2-eq ha^{-1} yr^{-1} (Fig. 6c).

The positive effect of increased use of synthetic N fertilization on N_2O emission is found in all scenario simulations regardless of crop residue and manure management (Fig. 7a). Under a certain N fertilization rate, increase in the rate of crop residue retention and/or manure application both increased the overall N_2O emission (Fig. 7a). The magnitude of enhanced N_2O emissions resulted from increased rate of crop residue retention and/or manure application were found smaller at

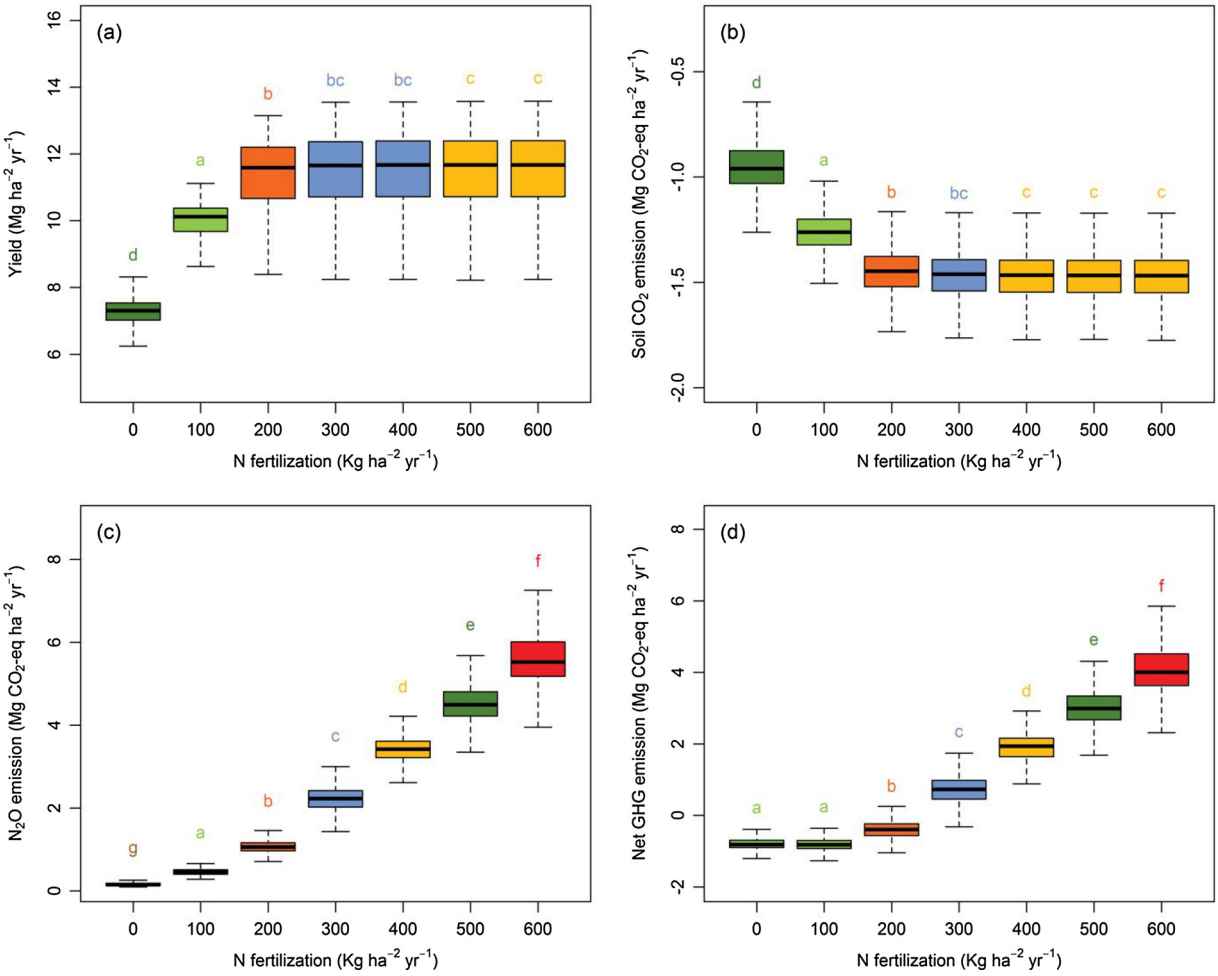
(a)
Yield (Mg ha^{-2} yr^{-1})
N fertilization (Kg ha^{-2} yr^{-1})
(b)
Soil CO_2 emission (Mg CO_2-eq ha^{-2} yr^{-1})
N fertilization (Kg ha^{-2} yr^{-1})
(c)
N_2O emission (Mg CO_2-eq ha^{-2} yr^{-1})
N fertilization (Kg ha^{-2} yr^{-1})
(d)
Net GHG emission (Mg CO_2-eq ha^{-2} yr^{-1})
N fertilization (Kg ha^{-2} yr^{-1})

Fig. 6. Effects of nitrogen fertilization on average crop yield (a), soil CO_2 emission (b), N_2O emission (c) and net greenhouse gas (GHG) emission (d). The soil CO_2 emission is the annual soil C loss in terms of CO_2-eq ha^{-1} yr^{-1}, positive and negative soil CO_2 emissions indicate the soil acted as a net source and sink of atmospheric CO_2. Data are derived from APSIM simulations under the scenario of 30% residue retention with the manure application rate of 2000 Mg ha^{-1} yr^{-1}. Apart from the synthetic N fertilization, additional N input from manure application (45 kg N ha^{-1} yr^{-1}) and N deposition (70 kg N ha^{-1} yr^{-1}) are adopted. Boxplots show the median and interquartile range, with whiskers extending to the most extreme data point within 1.5 × (75-25%) data range. Letters above each boxplot indicate significant differences between the means by Tukey's HSD post-hoc test, means that share the same letter are not significantly different from each other, means with different letters are significantly different ($P < 0.05$).

lower N fertilization rates and larger at higher rates of N use (Fig. 7a). Regardless of N fertilization, incorporating crop residues and/or manure into agricultural soils generally led to decreased soil CO_2 emissions (Fig. 7b), i.e., increased soil C stock or decreased loss of soil C. The use of N fertilizers was identified to have interactions with management of crop residue and manure in regulating soil CO_2 emission. For example, under R1_M0, the overall soil CO_2 emissions decreased along with increased N fertilization rate from 0 to around 300 kg ha^{-1} yr^{-1}, and changed little afterwards (Fig. 7b). Under R1_M2000, however, this decreasing trend tended to be stopped with a lower N fertilization rate (Fig. 7b).

The changes in net GHG emissions along with increased synthetic N fertilization rates generally exhibited a "decrease-increase" pattern, particular under higher rates of crop residue retention (Fig. 7c). The lowest net GHG emissions (-2.4 CO_2-eq ha^{-1} yr^{-1}) were found under R1 and M2000 with a N use rate of 75 kg ha^{-1} yr^{-1}, and the system would still act as a net GHG sink with increased N fertilization before a N use rate of around 340 kg ha^{-1} yr^{-1} was reached (Fig. 7c). Under the business-as-usual management of crop residues and manure (R0.3 and M2000), the lowest GHG emission was -0.9 CO_2-eq ha^{-1} yr^{-1} at the N rate of 60 kg ha^{-1} yr^{-1}, and net emission would remain negative before the N use was increased to 230 kg ha^{-1} yr^{-1} (Fig. 7c). With no crop residue retention and manure application (R0 and M0), the system acted as a net source of GHG, regardless of N use (Fig. 7c). In general, higher rates of crop residue retention generally resulted in lower net GHG emissions, particularly at lower rates of N fertilization (Fig. 7c). By contrast, the magnitude of increasing crop residue rate for decreasing net GHG emission were relatively smaller at higher N use rate (Fig. 7c). Similarly, the ability of manure application to reduce net GHG emissions were also lager at lower N use rates, while became smaller and even vanished at higher N fertilization rates (Fig. 7c).

Take the business-as-usual management as a starting point, both reducing N use and enhancing crop residue retention rate can lead to an overall reduction in the net GHG emissions (Fig. 7c). Accordingly, we seek to identify the needed N input rate under R1 and M2000 for both achieving the 90% of the maximum production (Fig. 8a) and the minimum net GHG emissions (Fig. 8b). Across the study area, the needed N rates for achieving these two targets were 132 (89–152) Kg ha^{-1} yr^{-1} and 74 (13–109) Kg ha^{-1} yr^{-1}, respectively (Fig. 8). In general, relatively smaller amount of annual N input was required in the north western than that in the south eastern region of the study area in order to achieve these two targets (Fig. 8a and b). By achieving these two targets, the crop yield would decrease from 11.2 (8.2–12.8, Fig. 9a) Mg ha^{-1} yr^{-1} under the business-as-usual management to 10.3 (7.7–11.7, Fig. 9b) Mg ha^{-1} yr^{-1} and 9.3 (6.6–10.8, Fig. 9c) Mg ha^{-1} yr^{-1}, respectively. The net GHG emissions would decrease from 0.70

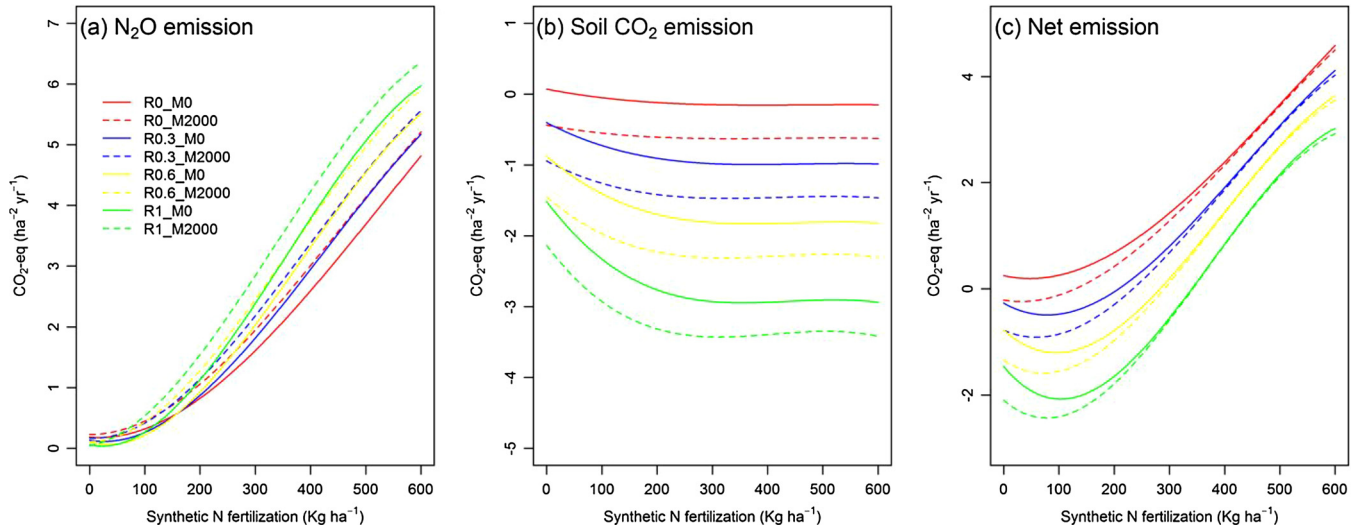

Fig. 7. Response of average crop yield (a), soil CO_2 emission (b), N_2O emission (c) and net greenhouse gas (GHG) emission to different management practices. The soil CO_2 emission is the annual soil C loss in terms of CO_2-eq ha^{-1} yr^{-1}, positive and negative soil CO_2 emissions indicate the soil acted as a net source and sink of atmospheric CO_2. R0, R0.3, R0.6 and R1 represent a crop residue retention rate of 0, 30%, 60% and 100%, respectively. M0 and M2000 represent a manure application rate of 0 and 2000 Mg ha^{-1} yr^{-1}, respectively. Apart from the synthetic N fertilization, additional N input from N deposition (70 kg N ha^{-1} yr^{-1}) across all scenarios, and that from manure application (45 kg N ha^{-1} yr^{-1}) under M2000 are adopted.The lines show the nonlinear least squares regression results based on the simulations of APSIM model.

(-0.08 – 1.33, Fig. 9d) Mg CO_2-eq ha^{-1} yr^{-1} to -2.27 (-2.81 – -1.88, Fig. 9e) Mg CO_2-eq ha^{-1} yr^{-1} and -2.47 (-2.93 – -2.13, Fig. 9f) Mg CO_2-eq ha^{-1} yr^{-1}, respectively.

3.5. Controls on the GHG emissions

Fig. 10 presents the impacts of rainfall, temperature and initial soil C stock on crop yields and GHG emissions on a regional scale under different management scenarios. In general, initial SOC positively correlated with all the three variables (Fig. 10). Temperature strongly and positively correlated with crop yield (Fig. 10a), moderately and positively correlated with soil CO_2 emission (negative emissions indicate soil carbon gain and *vice versa*, Fig. 10b) and not significantly correlated with N_2O emission (Fig. 10c). Rainfall displayed a strong and positive correlation with crop yield (Fig. 10a) and a negligible correlation with either soil CO_2 emission (Fig. 10b) or N_2O emission (Fig. 10c).

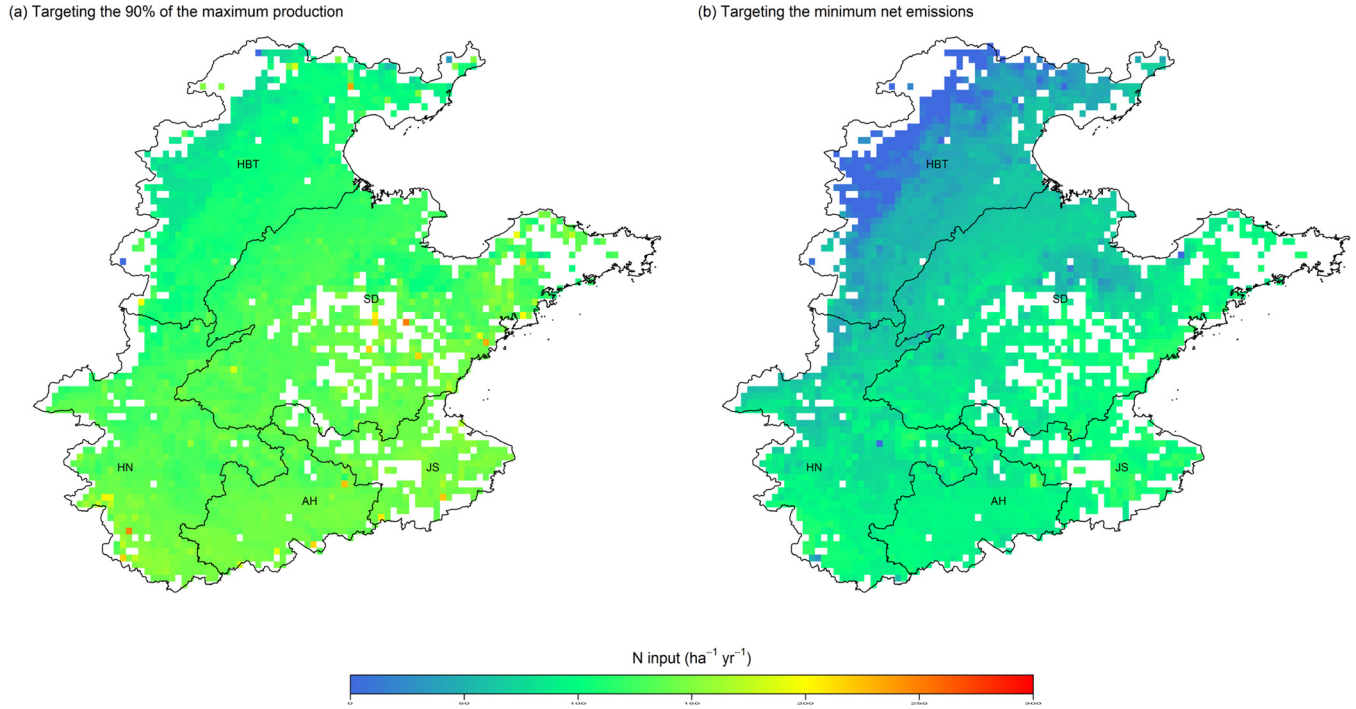

Fig. 8. Spatial distribution of nitrogen fertilizer demand for achieving the 90% of the maximum production (a) and the minimum net GHG emissions (b). Stubble retention rate is 100%, manure application rate is 2000 Kg ha^{-1} yr^{-1}. Apart from the synthetic N fertilization presented in the figure, additional N input from manure application (45 kg N ha^{-1} yr^{-1}) and N deposition (70 kg N ha^{-1} yr^{-1}) are adopted. The black lines for the HBT, SD, HN, AH and JS refer to the administrative regions of Hebei-Beijing-Tianjin, Shandong, Henan, Anhui, and Jiangsu, respectively.

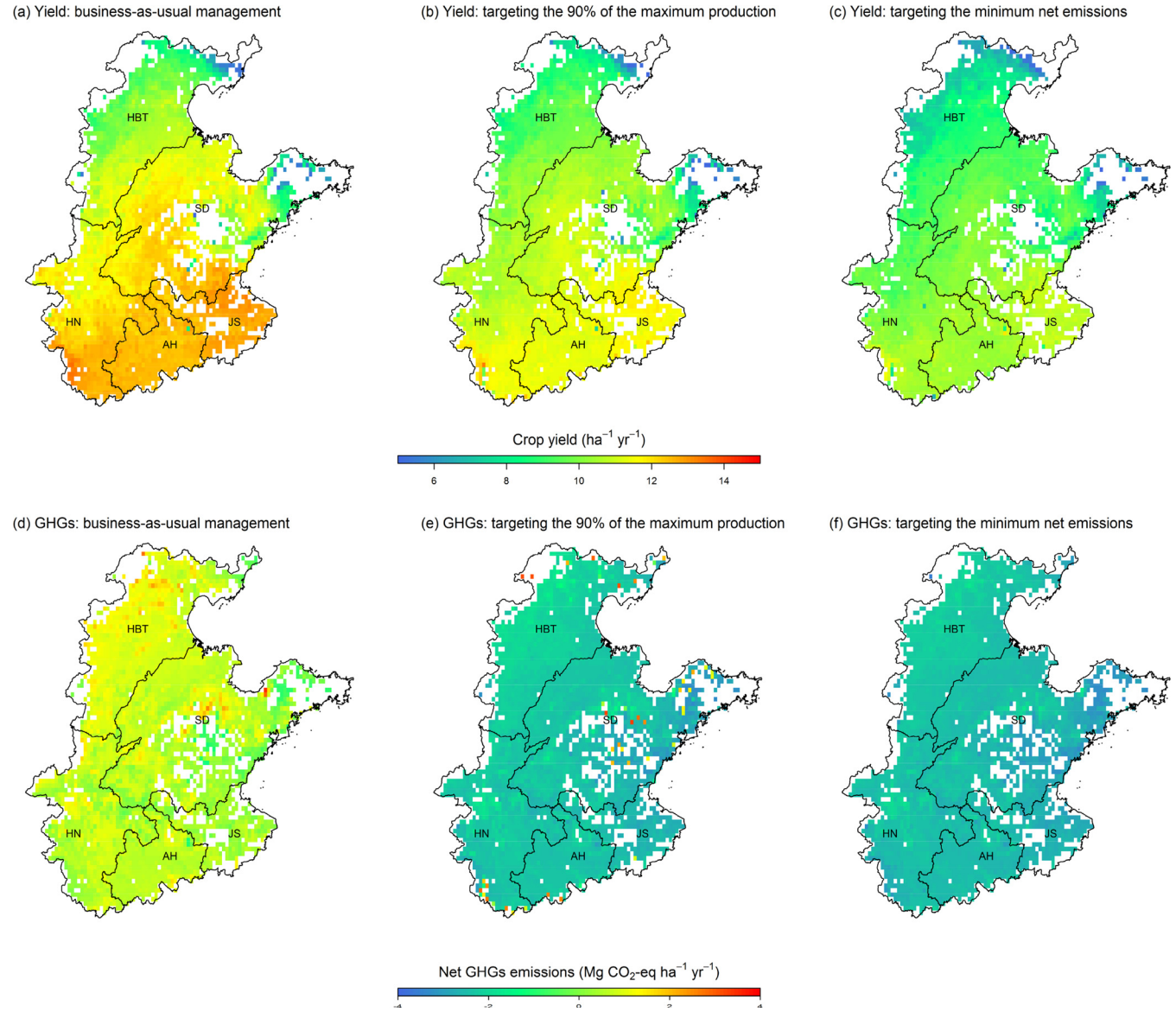

Fig. 9. Spatial distribution of average crop yield and GHG emission under different targets. (a) – (c) crop yield, (d) – (f) GHG emission. (a) and (d) are under business-as-usual management (N300, R0.3, M2000). (b) and (e) are for targeting the 90% of the maximum production under R1 and M2000. (c) and (f) are for targeting the minimum net GHG emissions under R1 and M2000. Stubble retention rate is 100%, manure application rate is 2000 Kg ha^{-1} yr^{-1}. Apart from the synthetic N fertilization, additional N input from manure application (45 kg N ha^{-1} yr^{-1}) and N deposition (70 kg N ha^{-1} yr^{-1}) are adopted. The black lines for the HBT, SD, HN, AH and JS refer to the administrative regions of Hebei-Beijing-Tianjin, Shandong, Henan, Anhui, and Jiangsu, respectively.

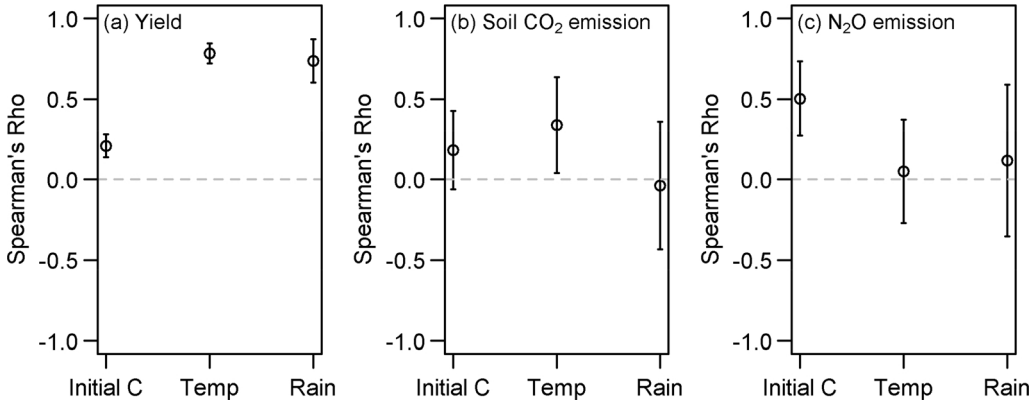

Fig. 10. The Spearman's correlation coefficients between crop yield (a), soil CO_2 emission (b) and N_2O emission (c) and the environmental conditions of initial soil organic carbon (*Initial C*), mean annual temperature (*Temp*), and mean annual precipitation (*Rain*). The soil CO_2 emission is the annual soil C loss in terms of CO_2-eq ha^{-1} yr^{-1}, positive and negative soil CO_2 emissions indicate the soil acted as a net source and sink of atmospheric CO_2. Circles and bars are average values and standard deviations for different scenario simulations.

4. Discussion

Apart from promoting N_2O emissions, the application of synthetic N fertilizers does enhance both crop yield and soil organic carbon sequestration (i.e., reducing soil CO_2 emission) (Fig. 6a and b). This is because N fertilization can improve soil nutrient conditions under nutrient deficiency, thereby increasing soil C content through increasing C inputs from crop residues and roots. It should be noted that this role can be weakened under the possible water deficiency in the future. Along with enhanced N fertilizations, irrigation has also been a major contributor to lifted crop productivity since the start of 1980s in this region, and excessive irrigation has resulted in cessation of river flows and depletion of groundwater resources (Wang et al., 2008). Unlike N fertilizers that can be produced through manufacturing, overused irrigation water may not be readily recoverable and lead to an unsustainable agricultural production. In such case, the ability of improving N fertilization to enhance crop yields and SOC levels would be limited.

Even with sufficient water supply, our results demonstrated that increasing N input does not always promote crop growth and soil C sequestration, particularly with an N use rate higher than 300 kg ha^{-1} yr^{-1} (Fig. 6b). This is consistent with our previous work using another process-based agricultural system model (i.e., Agro-C) (Wang et al., 2014b). For the crop yield in response to N fertilization, it has been reported that yields above 90% of the maximum yield are associated with significantly diminished economic return (Carberry et al., 2013). In our simulations, we found that the modelled highest average crop yield (sum of wheat and maize) was about 11.2 Mg ha^{-1}, and a 90% of the maximum yield was reached at a synthetic N rate of 132 kg ha^{-1} (Fig. 8a). Here, taking the N input from atmosphere and manure into consideration, our results suggested that the total yield of 10.3 Mg ha^{-1} under the total N input of 247 kg ha^{-1} (132 kg ha^{-1} from synthetic N fertilizer, 70 kg ha^{-1} from N deposition and 45 kg ha^{-1} from manure) in the double cropping systems of HHH Plain. It should be noted that synthetic N fertilization is also one of the key sources of N deposition, and the amount of N deposition would be decreased with reduced N fertilization rates. Moreover, the application rate of manure would be significantly decreased during the process of urbanization. Consequently, to achieve 90% of the maximum yield in a real world, a higher synthetic N fertilization rate than that quantified in the present study (i.e., 132 kg ha^{-1}) would be needed. This is also the case for the needed N use rates to achieve the lowest GHG emissions during agricultural production.

The current synthetic N fertilization (with an average rate more than 300 kg ha^{-1}) has been overused in terms of economics according to our estimates. Even with such a high level of N input, the contemporary (1981–2010) statistical average yield reaches about 7.8 Mg ha^{-1}, which is even lower than 90% of our simulated maximum yield (10.3 Mg ha^{-1}, Fig. 9b). This is consistent with the report of Zhang et al. (2016), who stated an average difference of about 25% between the experimental yield and the yield farmer could expect from the same management practices. Such a gap could be attributed to several other relevant factors influencing crop growth such as extreme weather conditions, crop diseases and suboptimal management (Doltra et al., 2011; Ewert et al., 2002; Liu et al., 2011; Miguez et al., 2012; Rötter et al., 2012). Our simulation results support the suggestion that this gap can be closed by improving site-specific management practices (Zhang et al., 2016).

Increased use of N at rates higher than 200 Mg ha^{-1} dramatically and linearly increased N_2O emissions (Figs. 6c and 7a), this promoting effect has been widely found by other studies (Li et al., 2016a; Lu et al., 2006; Luo et al., 2017). Our simulation results suggested under R0.3 and M2000, a 50% reduction of current N use rate (from 300 kg ha^{-1} to 150 kg ha^{-1}) can reduce around 67% of the N_2O emissions without sacrificing the economic return from grain yield (i.e., maintaining a higher yield than 90% of the maximum simulated yield). By doing this, although soil C sequestration rate decreased by about 8% subjected to less C input to soils contributed by crop residues and roots, the net GHG emissions decreased from 0.70 (i.e., a net source of GHG) to -0.64 CO_2-eq ha^{-1} yr^{-1} (i.e., a net sink of GHG).

Under the business-as-usual management (N300, R0.3, M2000), our simulations suggested that average annual soil CO_2 emission rate was -1.53 CO_2-eq ha^{-1} yr^{-1} (Fig. 7b), indicating soil annually sequestrated 0.41 Mg C ha^{-1}. This is consistent with the findings (0.31 Mg C ha^{-1} yr^{-1}) of a recently published literature (Han et al., 2018) and our previous work (0.35 Mg C ha^{-1} yr^{-1}), both focusing on the SOC dynamics in North China Plain. The relatively higher value in this study may due to a higher crop residue retention rate was used in the present study (30%), while lower values (20%–30%) were adopted in those two works. In term of global warming potential, our simulations suggested that the current annual soil C sequestration could only compensate around 68% of the annual N_2O emissions and the agricultural system acted as a net source of GHG (Fig. 7). This further highlights the importance of taking into account the negative effect of N fertilizers on environment such as GHG emissions for sustainable agricultural intensification.

Along with the reduction of N use, increasing crop residue retention rate can also reduce the net GHG emissions owing its ability to promote soil C sequestration (Fig. 7c). For example, under N300 and M2000, the average net emission would decrease from 0.73 to 0.26 and -0.37 CO_2-eq ha^{-1} yr^{-1}, under R1, R0.6 and R0.3, respectively (Fig. 7c). With a 50% reduction in N use, this would further be decreased to -1.35 and -2.19 CO_2-eq ha^{-1} yr^{-1} under R0.6 and R1, respectively (Fig. 7c). Application of manure could also reduce the net GHG emissions, particularly at lower rates of N application (Fig. 7c). This is because manure contains C and N, which can not only directly add C into soils but also improve crop production thereby providing more C input to soils from crop residues and roots. At higher rates of N use, this effect seems to be limited (Fig. 7c) because N_2O emission (Fig. 7a) and soil C sequestration (Fig. 7b) introduced by manure application cancelled each other.

There does exist opportunities for both maintaining crop production while significantly reducing current GHG emissions from the agricultural systems. Compared to the business-as-usual management, by adopting 100% stubble retention rate and reducing the N use rate by ~ 55%, 90% of the maximum yield can be achieved (Fig. 9b) while turning the system from a source (0.70 Mg CO_2-eq ha^{-1} yr^{-1}, Fig. 9d) to a sink (-2.27 Mg CO_2-eq ha^{-1} yr^{-1}, Fig. 9e) of GHGs. Targeting the minimum net GHG emission is feasible by further reducing N input rates, however, this would result in a 17% reduction in crop yield compared to the maximum modelled yield (Fig. 9d). Again, the uncertainties and limitations of the quantified N rates should be noted. Because N deposition rate could be changed with varied synthetic N rates, a higher rate than that estimated in the present study would be needed to ensure achieving the targeted crop yields.

Across space, we found that initial soil C is slightly and positively correlated with crop yield (Fig. 10a), which is consistent with findings of Pan et al. (2009), who reported that soil C can benefit crop productivity. The positive correlations between initial soil C and soil CO_2 emission (Fig. 10b) is because, under otherwise similar environmental and managed conditions, cropland soils with higher initial carbon content would experience greater SOC loss (Wang et al., 2014b), i.e., smaller soil CO_2 emission (negative emissions indicate soil carbon gain and *vice versa*). Moreover, the nitrifiers and denitrifiers use soil organic carbon as a source of C and energy during the processes involved with N_2O production (Azam et al., 2002; Weier et al., 1993), this explains the positive correlation between initial soil C and N_2O emission (Fig. 10c). The positive effect of temperature on crop yield (Fig. 10a) as found in the present study is consistent with the findings of Mo et al. (2009), who reported that climate change over the second half of last century (characterized mainly with a rising temperature) turned to be favorable to crop productions in the North China Plain. Higher temperatures

would increase actual soil C decomposition rate and promoting more soil CO_2 emission (Fig. 10b), this is consistent with the findings of Meersmans et al. (2011). The positive effect of rainfall on crop yield (Fig. 10a) could be misleading because rainfall had a positive correlation with temperature in the HHH plain (Fig. A1 in Appendix A). The effects of rainfall were likely to be over shaded by irrigation, which brings soil moisture to field capacity when it drops to 70% of the field capacity. In this case, the crop would meet no water stress, regardless of rainfall. However, the radiation would be weakened with more rainfall, which caused a lower level of crop productivity.

Higher rainfall has been reported to be able to promote both soil CO_2 and N_2O emissions (Luo et al., 2017). This impact, however, were not found in the present study. This could also be attributed to irrigation. In areas with less rainfall, irrigation would be more frequently adopted. And the wet-dry cycles in the soil profile have been proved to enhance the amplitude of CO_2 pulses as well as promoting nitrification and N_2O emissions (Fierer and Schimel, 2002), thereby resulting in a negligible correlation between rainfall and both soil CO_2 and N_2O emissions (Fig. 10). It should be noted that irrigation practice could be abandoned in the future because the overuse of irrigation has resulted in cessation of river flows and depletion of groundwater resource (Wang et al., 2008). By then, rainfall will be the main water resource for agricultural system, which would likely has positive effects on soil CO_2 and N_2O emissions. Soil microbes play a central role in soil organic carbon dynamics and N_2O emission via a series of soil processes such as humification, decomposition, nitrification and denitrification. These microbial processes are regulated by soil environmental conditions such as soil temperature and moisture (Weitza et al., 2001; Yao et al., 2010). In the arid and semi-arid regions (e.g., the HHH Plain), increasing soil water availability (e.g., irrigation) would certainly provide a more favourable environment for microbial activities, stimulating both soil CO_2 and N_2O emissions. Meanwhile, the amount of both crop yield and residue would also be increased with more favourable soil moisture conditions, the crop residues can be incorporated into soils and thereby promoting soil organic carbon sequestration and offsetting GHG emissions. The interplay between net soil GHG emissions and soil moisture needs a further study in the future. Furthermore, we didn't take conservation tillage into consideration in the present study, which might cause possible uncertainties in the simulations. However, our results could still be robust across most parts of the study region because the average fraction of the area adopting conservation tillage in Chinese croplands was less than 10% during the study period (Yu et al., 2012). Moreover, precious studies have suggested that conversion from conventional tillage to conservation tillage mainly causes redistribution of soil C in the soil profile with limited influence on total SOC stock (Luo et al., 2010).

Last but not least, in terms of uncertainty sources, in this study, we only explicitly assessed the uncertainty induced by model parameterization. We note that the uncertainties induced by model structure and model inputs are also important but may have limited effects in this study. For model structure, in the present study, we calibrated the APSIM model against field observations at three sites located in the study region, and the time span of the data for the calibration is consistent with the regional simulations (i.e.,1980–2010). Along with a number of other studies demonstrating the credibility of the APSIM model in simulating farming systems, the well performance of the model (Fig. 3) further suggests that the model and thus its structure is robust to simulate the double wheat-maize cropping system. Here, we acknowledge that when more field observations become available, the performance of the model can certainly be further improved, and, if extending the simulation to longer time frames, a multi-model comparison with different model structure will provide additional information on the relevant uncertainties. For model inputs, the spatial soil properties and climate data (Fig. A1 in Appendix A) adopted in the study have been widely used for modelling (Yu et al., 2012; Qin et al., 2013; Wang et al., 2014b). More importantly, these data layers are derived based on observational data set. Agricultural management is another set of model inputs, as suggested by Yu et al. (2012), agricultural management such as stubble retention, N fertilization and manure application are of the largest uncertainties in simulating regional cropland soil processes. In the present study, these agronomic practices were considered by the comprehensive scenario analyses.

5. Conclusions

Under the traditional agricultural management practices, we found that cropland soils in the Huang-Huai-Hai Plain of China sequestered carbon with an annual rate of 1.53 CO_2-eq ha^{-1} yr^{-1} (0–30 cm soil layer) over the period of 1981–2010. However, nutrient input such as synthetic N also significantly accelerated other greenhouse gases such as nitrous oxide (N_2O), and only about 68% of global warming potential from contemporary N_2O emissions in the HHH Plain could be cancelled by soil carbon sequestration. There exists opportunities for reducing greenhouse gas emissions without sacrificing grain yield, e.g., reducing the nitrogen input rate together with enhancing crop residue retention rate. When developing management practices for maintaining yield, stimulating carbon sequestration as well as reducing N_2O emissions, environmental factors (e.g., rainfall, temperature and initial soil C stock) must be considered as their significant effects on the dynamics of crop yield, soil CO_2 and N_2O emissions.

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Appendix A

Table A1
The 100 optimised values of APSIM parameters in simulating soil carbon dynamics.

CUE	rd_hum	finert	CUE	rd_hum	finert
0.449	0.000077	0.459	0.435	0.000071	0.730
0.443	0.000076	0.503	0.426	0.000052	0.365
0.447	0.000074	0.430	0.425	0.000063	0.470
0.452	0.000083	0.520	0.431	0.000063	0.730
0.446	0.000083	0.505	0.422	0.000042	0.433
0.453	0.000088	0.521	0.425	0.000043	0.603
0.439	0.000071	0.467	0.449	0.000057	0.314

(*continued on next page*)

Table A1 (*continued*)

CUE	rd_hum	finert	CUE	rd_hum	finert
0.447	0.000074	0.569	0.428	0.000042	0.545
0.442	0.000063	0.420	0.467	0.000097	0.567
0.448	0.000082	0.421	0.426	0.000060	0.394
0.453	0.000095	0.524	0.457	0.000074	0.573
0.449	0.000092	0.566	0.428	0.000071	0.483
0.446	0.000088	0.483	0.475	0.000116	0.444
0.434	0.000054	0.458	0.465	0.000085	0.283
0.452	0.000076	0.556	0.426	0.000040	0.570
0.430	0.000055	0.539	0.436	0.000058	0.709
0.463	0.000097	0.443	0.431	0.000055	0.724
0.431	0.000054	0.537	0.470	0.000116	0.422
0.427	0.000055	0.524	0.431	0.000043	0.275
0.433	0.000061	0.408	0.425	0.000045	0.314
0.459	0.000103	0.479	0.456	0.000070	0.233
0.460	0.000094	0.560	0.429	0.000039	0.347
0.427	0.000051	0.522	0.440	0.000048	0.512
0.462	0.000106	0.521	0.442	0.000052	0.568
0.457	0.000085	0.583	0.443	0.000051	0.251
0.441	0.000077	0.402	0.417	0.000048	0.681
0.461	0.000101	0.412	0.464	0.000079	0.477
0.437	0.000065	0.676	0.473	0.000119	0.543
0.440	0.000088	0.616	0.444	0.000086	0.364
0.449	0.000067	0.291	0.426	0.000039	0.564
0.428	0.000060	0.669	0.462	0.000101	0.325
0.428	0.000055	0.396	0.447	0.000086	0.329
0.454	0.000083	0.631	0.420	0.000051	0.406
0.459	0.000076	0.466	0.422	0.000040	0.340
0.423	0.000051	0.617	0.433	0.000073	0.767
0.422	0.000046	0.515	0.431	0.000040	0.273
0.424	0.000057	0.469	0.424	0.000036	0.368
0.448	0.000058	0.332	0.475	0.000122	0.515
0.449	0.000073	0.643	0.420	0.000052	0.408
0.423	0.000061	0.603	0.414	0.000042	0.558
0.446	0.000076	0.305	0.464	0.000088	0.594
0.430	0.000074	0.663	0.416	0.000052	0.689
0.446	0.000082	0.344	0.454	0.000060	0.424
0.437	0.000083	0.681	0.440	0.000055	0.194
0.468	0.000114	0.515	0.462	0.000120	0.552
0.427	0.000058	0.702	0.445	0.000049	0.267
0.440	0.000064	0.279	0.432	0.000052	0.234
0.424	0.000042	0.434	0.449	0.000052	0.352
0.442	0.000052	0.292	0.414	0.000051	0.644
0.434	0.000074	0.722	0.414	0.000054	0.371

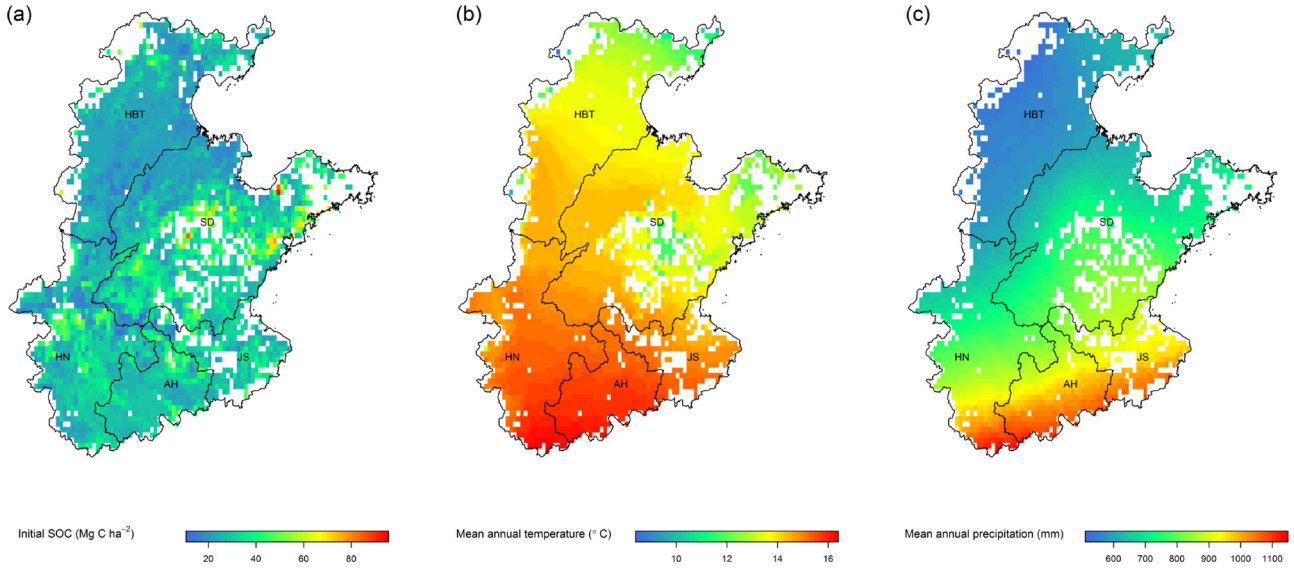

Fig. A1. Spatial map of initial soil organic carbon content in the top 30 cm (a), mean annual temperature (b), and mean annual precipitation (c) over the study period (i.e., 1981–2010) in the cropping systems of HHH Plain.

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